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# Plate Motions and Deformations from Geologic and Geodetic Data

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## 1. SIGNIFICANT ACCOMPLISHMENTS

This Semiannual Report covers research conducted under NASA Contract NAG5-459 for the period 1 January through 30 June 1990.

We have continued the analysis of geodetic data in the vicinity of the CDP site at Vandenberg Air Force Base (VNDN). The data include historical land-based geodetic surveys conducted since the late nineteenth century and recent space-geodetic data sets, including both VLBI-determined station positions and GPS surveys. Preliminary results were discussed in a paper by Feigl, King and Jordan [1990], published in the March issue of the Journal of Geophysical Research.

We are also investigating the utility of space-geodetic data in the monitoring of transient strains associated with earthquakes in tectonically active areas like California. We are particularly interested in the possibility that space-geodetic methods may be able to provide critical new data on deformations precursory to large seismic events. Although earthquake precursory phenomena are not well understood, the monitoring of small strains in the vicinity of active faults is a promising technique for studying the mechanisms that nucleate large earthquakes and, ultimately, for earthquake prediction. Space-geodetic techniques are now capable of measuring baselines of tens to hundreds of kilometers with a precision of a few parts in 108. Within the next few years, it will be possible to record and analyze large-scale strain variations with this precision continuously in real time. Thus space-geodetic techniques may become tools for earthquake prediction. In anticipation of this capability, we are examining several questions related to the temporal and spatial scales associated with subseismic deformation transients.

A recent paper co-authored by the P.I. discussing some of the research sponsored by this contract is included as an Appendix.

## 2. PROBLEMS AND RECOMMENDATIONS

None

## 3. DATA UTILITY

Not applicable

## 4. FUNDS EXPENDED

As of 30 June 1990 a total of $402,559 had been spent, out of the current fund limitation of $471,075.

In Geodesy in the Year 2000, ed. by J.B. Rundle, National Academy Press, Washington, D.C., 1990.

# Implications of Precise Positioning

**Jean-Bernard H. Minster, Thomas H. Jordan, Bradford H. Hager, Duncan C. Agnew, Leigh H. Royden**

## INTRODUCTION

One of the most exciting developments in crustal kinematics over the last two decades has been the birth of space-geodetic positioning techniques capable of achieving accuracies of one cm or better. The principal motivation for using these techniques for precise point positioning is to take advantage of the significant increase in technological capabilities that they represent in order to address directly important tectonic problems that cannot be tackled economically at present by ground-based geodetic techniques and classical field geology. The main techniques which have matured over the past decade or so include *Very Long Baseline Interferometry* (VLBI) and *Satellite Laser Ranging* (SLR).

More recently, the less burdensome--from the point of view of field operations--*Global Positioning System* (GPS) has gained considerable popularity for the study of regional deformation problems. Over the technological and scientific horizon, we may count as future candidates the *Geodynamic Laser Ranging System* (GLRS) which is being considered as a facility instrument on the EOS platform, as well as alternatives developed in Europe, such as the French DORIS and the German PRARE systems. Convenience considerations aside, the main advantage of these new techniques, from the geologist's point of view, is that they should permit (in principle) *frequent* resurveys of *dense* networks. This, together with improved control of vertical displacements, represents a completely new, enhanced capability, which will allow geologists to address problems that have so far eluded them.

It may seem difficult to believe that the ability to measure the relative positions of two points on the earth separated by 100 or even 10,000 km has a measurable socio-economic impact. The applications to earthquake prediction and volcanic surveillance are, of course, often invoked, but somehow seem too remote to justify an immediate development effort. Nevertheless, in the past decade, space geodesy has begun to provide useful constraints on the solution of difficult geological problems of immediate importance, such as the distribution of crustal deformation both east and west of the San Andreas Fault in central California (e.g., Jordan and Minster, 1988b). This issue is an interesting one from a scientific point of view, but it also has great practical importance, in view of the high population density and numerous critical facilities found along the Pacific coast of the U.S. In the next two decades, we must extend our experience to other tectonically active areas which have significant human as well as scientific importance.

## CRUSTAL MOTIONS AND DEFORMATIONS

Deformation of the earth's lithosphere covers a broad spectrum of temporal and spatial scales, from seconds to aeons and from mineral grains to planetary dimensions. We rely below on the discussion of Jordan and Minster (1988a).

Table 1 categorizes a subset of lithospheric motions that cause geologically and geophysically significant deformations. It is convenient to discriminate secular motions persisting on geological time scales of thousands to millions of years from transients associated with, for example, seismic and volcanic events. Practical research is more concerned with the transients, because they tend to disturb human activities. Secular motions also warrant vigorous study, however, since they provide the kinematical framework for describing transients and understanding their driving mechanisms.

The most significant long-term deformations are those related to plate tectonics. Although local tectonic movements near plate boundaries display large vertical components and time-dependent behavior, the net motions between the stable interiors of large blocks are forced by viscous damping and gravity to be nearly steady and horizontal. The characteristic tangential velocity of the plate system is about 50 mm/yr, which gives rise to displacements easily measured by *geodetic* methods. Horizontal secular motions have been observed both by ground-based networks (e.g., Savage, 1983) and by space-geodetic systems (e.g., Christodoulidis et al., 1985; Herring et al., 1986). Though their application to geodesy is relatively new, space-based techniques have already revolutionized the science of terrestrial distance measurement. They are contributing new information about active tectonics, particularly on the planetary scales previously inaccessible to ground-based surveys (Figure 1).

Rigid-plate motions. In the ocean basins, most of the deformation related to horizontal secular motion occurs in well-defined, narrow zones that are the boundaries of a dozen or so large lithospheric plates. The current plate velocities are constrained by three basic types of data collected along these submerged boundaries: (1) spreading rates on mid-ocean ridges from magnetic anomalies, and directions of relative motion from (2) transform-fault azimuths and (3) earthquake slip vectors. The first self-consistent global models were synthesized soon after the formulation of plate tectonics (LePichon, 1968), and significant refinements were made throughout the next decade (Chase, 1972; Minster et al., 1974). Third generation models were published by 1978 (Chase, 1978; Minster and Jordan, 1978) and are still in use. Work has been recently completed at Northwestern University on an improved fourth-generation plate-motion model name NUVEL-1 (DeMetz et al., 1989), which remedies most of the problems identified with earlier models (see also Gordon et al., 1988).

Since the reference frame is arbitrary, the angular velocity vectors describing the instantaneous relative motions among $M$ rigid-plates are specified by $3(M - 1)$, independent components, which are derived by least-squares inversion of a carefully selected, globally distributed data set. As shown in Table 2, the increasing sizes of the data sets upon which successive generations of models have been based reflect continued vigorous research activity in geology and geophysics since the advent of plate tectonics.

Table 3 lists the instantaneous rotation vectors ("Euler vectors") that describe the relative motions of the plates in NUVEL-1. It is reproduced from the presentation by R. Gordon and his co-workers at the October 17-21, 1988 NASA Crustal Dynamics Principal Investigators Meeting, held in Munich, Germany (Gordon et al., 1988). The convention adopted in this table is that the first plate moves counterclockwise relative to the second plate. The nomenclature is as follows: af - Africa, an - Antartica, ar - Arabia, au - Australia, ca - Caribbean, co - Cocos, eu - Eurasia, in - India, na - North American, nz - Nazca, pa - Pacific, sa - South America. Table 3 also lists the one-sigma error ellipses (marginal distributions) attached to the Euler vector estimates. The two-dimensional marginal distribution of the pole position is specified in each case by the angular lengths of the principal axes and the azimuth $\xi_{max}$ of the major axis, and the one-dimensional marginal distribution of the angular rotation rate is specified by its standard deviation $\sigma_{\omega}$.

The magnetic anomalies employed in the various rigid-plate motion models mentioned above average the rates over the last 2-3 million years, about the shortest time span for which good spreading rates can be obtained on a global basis. Although this interval is hardly "instantaneous" from a geodetic point of view, it is geologically brief, and the small plate displacements that take place during it are well described by infinitesimal (as opposed to finite) rotations. It will probably be some time before the global plate-tectonic models can be significantly improved by space geodesy. Because the geological data sets are large and the inverse problem is strongly overdetermined, the formal uncertainties in the angular velocity components are already quite small, and correspond to formal uncertainties of 1 or 2 mm/yr in the predicted rates of relative motions. More importantly, the fourth generation NUVEL-1 model listed in Table 3 is *consistent*, at the 1-2 mm/yr level, with the hypothesis that major plates behave *rigidly* over a million-year time scale. Moreover, there is growing evidence that the rates-of-change of geodetic baselines spanning plate boundaries are consistent with the geological estimates (e.g., Herring et al., 1986), provided that the endpoints are located within stable plate interiors. (This is comforting, both as a check on the techniques and as corroboration of the geophysical expectation that the instantaneous velocities between points in stable plate interiors are dominated by secular plate motions.) This means that, for those plates whose motions are well constrained by geological observations, direct geodetic measurements will not add significant constraints to the estimate of secular velocities. In any case, given the level of internal consistency of the geological models, to contribute to the improvement of existing models of present-day motion among the major plates, the tangential components of relative velocities on interplate baselines with endpoints located within stable plate interiors must be resolved to an accuracy on the order of 1 mm/yr.

It is therefore clear that geologically-based global plate motion models provide in fact a *kinematic reference frame* in which to analyze short-term geodetic observations, as well as the *kinematic boundary conditions* which must be satisfied by models of plate boundary deformation zones. In other words, the most important and interesting geodetic signals with characteristic time scales ranging from 1 hour to 100 years are detected as *departures* from predictions of million-year average rates based on geological rigid-plate models.

However, there exist examples for which the reliability of currently available global models is difficult to assess, and some improvement could be made from space-geodetic data. For example, Southeast Asia is assumed to be part of the large Eurasian plate, but the active tectonics of China imply it should be moving as a separate entity. Because it is completely surrounded by complex zones of deformation, its motion relative to Eurasia will be difficult to quantify without space-geodetic observations. Similarly, we note that geological rates are lacking across convergent boundaries, such as trenches. This is one reason why the motion of the Philippine plate relative to its neighbors is not well known. Again, space geodesy should provide useful constraints. Closer to home is the case of the Pacific-North America plate pair, whose relative rate of motion can be directly measured only on a tiny ridge segment in the mouth of the Gulf of California. The recent modeling work of DeMetz et al. (1987) (reflected in NUVEL-1) yields a relative plate velocity along that boundary that is 15-20% slower than earlier estimates. Since this rate is critical to models of deformation in the western United States, a geodetic check on the Pacific-North America angular velocity will be very valuable.

With these exceptions and a few others, however, the global networks of VLBI and SLR stations are just too sparse to control plate motions as tightly as the geological observations. The impact of geodetic observations on the development of these plate-motion standards will be relatively minor, at least for the next few years. Of course, this does not say that interplate observations made by space-geodetic methods will not reveal new and interesting phenomena associated with other categories of motion listed in Table 1; particular attention should be focused on time-dependent signals, including the possibility that plate speeds and directions have changed significantly during the 2-My averaging period of the geological data. Our point is to emphasize that *the exciting issues for space geodesy lie beyond the now-classical descriptions of major plate motions*.

Departures from rigid-plate motions. The various types of departures from the predictions of the rigid-plate models fall into two major categories: (1) large scale and regional scale non-rigid behavior (plate deformation and plate boundary zones of deformation), and (2) non-steady motions, including in particular post-seismic strains and aseismic deformations.

**Plate deformation.** There are conspicuous instances where the ideal rigid-plate model fails to describe adequately the complexities of present-day tectonic interactions, especially within the continents and along their margins. Examples can be found in regions undergoing compression due to plate collision, such as the Alpide Belt, and more particularly, Tibet, or the northern margin of the South American plate, as well as regions dominated by extensional tectonics, such as the African Rift Zone and the western U.S. Such regions are often characterized by spectacular landscapes and have long attracted the attention of geologists.

Perhaps the most outstanding example of large-scale continental deformation is Tibet. Collision of the Indian subcontinent with the Asian continent about 50 million years ago has been followed by roughly 2000-4000 km of convergence across Tibet and the Himalayas, resulting in the most impressive region of young and active deformation on earth (Molnar and Tapponnier, 1975, 1978). Although it is generally accepted that deformation within Tibet has resulted in movement of crustal fragments, with dimensions of tens to hundreds of kilometers, in directions oblique or even orthogonal to the overall direction of convergence between India and Asia, the details of present rates and directions of motion are still sketchy at best (e.g., Lyon-Caen and Molnar, 1985; Molnar et al., 1987). The use of space-geodetic techniques to unravel the complex kinematical picture of this region, even at the reconnaissance level of detail, should certainly be recognized as an important target for the next two decades.

Another young example of active tectonics which space geodesy will help understand better is the Mediterranean region. There we have "back arc" type basins adjacent to zones of coeval subduction and convergence, such as the Aegean-Hellenic systems, the Tyrrhenian-Appennine/Calabrian system, and the Pannonian-Carpathian system (see, for example, Malinverno and Ryan, 1986; McKenzie, 1972, 1978; Mercier, 1977; Royden et al., 1983; Scandone, 1979). These continental systems present an excellent opportunity to study the interaction of active extensional and convergent processes because, unlike most oceanic systems, a reasonably large amount of the region is exposed above sea-level, so that geodetic and geologic field studies are practical. Again the importance of reaching a more precise understanding of the current tectonic evolution of the area is enhanced by the high population density. Accordingly, a substantial long-term multi-national effort, the Wegener-Medlas Project, has been undertaken in 1984 to refine the kinematic picture of the Mediterranean region, and has begun to yield SLR data capable of placing useful constraints on the geological models (e.g., Wilson, 1987). The continuation of this project on a regional scale, and the densification of the network in critical areas (using, for example, GPS campaigns) will remain an important component of tectonic studies of the region in the coming years.

A particularly interesting third example is the western United States, where the interaction between the North American plate and the northwestward moving Pacific plate is spread out over broad zones of deformation, and where the available geodetic data sets are substantially larger. Although California's San Andreas Fault can be identified as a major locus of movement on the Pacific-North America plate boundary, the likelihood that significant crustal deformation is occurring both east and west of the San Andreas has long been recognized by geologists. Geological and geodetic observations of the present rate of slip along the fault in central California (about 34 mm/yr) is significantly lower than the rate predicted from successive generations of rigid-plate motion models, including NUVEL-1 (about 50 mm/yr). This so-called "San Andreas discrepancy" has been analyzed by Minster and Jordan (1984, 1987), using both geological information and geodetic data. Their conclusion was that even the short 4 year record of VLBI observations available to them for the relevant baselines (see Figure 2) was sufficient to place useful constraints on the integrated deformation east of the San Andreas across the Basin and Range, and by vector addition, on the integrated deformation west of the San Andreas across the California margin (see also Weldon and Humphreys, 1985).

Jordan and Minster (1988a) reviewed the use of space-geodetic observations to solve geological problems, with a focus on the various types of *secular horizontal* motions listed in Table 1. They concluded that many geological and geophysical problems related to such motions are indeed currently being addressed by space-geodetic experiments, provided that critical measurements are made at accuracies not feasible by conventional techniques. In particular, they state that measuring the velocities between crustal blocks to ±5 mm/yr can place geologically useful constraints on the integrated deformation rates across continental plate-boundary zones, such as the western U.S., the Mediterranean and Tibet.

However, it must be emphasized that baseline measurements in geologically complicated zones of deformation are useful only to the extent that the relationship of the endpoints to geologically significant crustal blocks is understood. Some antennas have a long history of participation in VLBI experiments, so that their motions in the VLBI reference frame are becoming well known; but they lie within complex zones of faulting, and their motions in kinematical frames fixed to local geology are not at all known. For example, the baseline rates for the Owens Valley Radio Observatory (OVRO) in California relative to the Westford, Massachusetts, and Ft. Davis, Texas, antennas have been measured to a precision of about 2 mm/yr (Figure 2). In their analysis of Basin and Range extension, Minster and Jordan (1987) have assumed OVRO moves with the Sierra Nevada-Great Valley block, but unfortunately, it is separated from the Sierra Nevada by a major system of faults, one of which broke in the great 1872 Owens Valley earthquake. Until the position of OVRO is regularly resurveyed in a local geodetic network which includes stations planted firmly on the Sierra block, the geological implications of the VLBI data will remain in doubt. Consequently, we can recommend that the establishment of frequently (or even continuously) surveyed local geodetic networks of sufficient density, around major geodetic sites in active areas should receive high priority.

The discussion has been focused so far on rather localized deformation, that is, on the occurrence of deformation zones with horizontal scales significantly less than overall plate dimensions. Whether the major tectonic plates, which are found to behave rigidly to an excellent approximation over million-year time scales, are actually undergoing nonlocal steady or episodic deformation on shorter time scales, is another important scientific question which bears directly on our understanding of the mechanical behavior of the lithosphere on a large scale, as well as our models of the force systems that drive plate tectonics. In order to resolve this issue, we will require geodetic coverage on a *global* scale, using techniques capable of delivering mm/yr accuracy for baselines 10,000 km long. Only space geodesy can meet such requirements, and, in the absence of any kind of "ground truth", we must rely on intercomparisons between independent techniques to evaluate the actual performance of the systems.

**Nonsteady motions**. The problems of time dependence of the motions and non-rigid behavior of the plates, two issues which lie beyond the now-classical descriptions of major plate motions, are exciting applications of current and future space geodetic systems. The fundamental underlying scientific problem is the *transmission of strain (or stress)* in the lithosphere. This question is intimately related to the problem of coupling between earthquakes, evolution of volcanic eruption, and ultimately to the problem of *predicting* catastrophic events.

The time scales involved range from a fraction of an hour to centuries or longer, and span a range in which the physical phenomena are very poorly understood, primarily because the measurements are sparse, infrequent, and mostly very recent. Thus the evidence for episodic (as opposed to steady) motions along plate boundaries and within plate boundary deformation zones is insufficient at the present time to map the time and spatial scales involved.

A space-geodetic system capable of high sampling rate and dense spatial coverage over large areas will make possible a nearly unprecedented exploration of how crustal deformation varies with time. Much too little is known about this, the only data so far available comes from geodetic measurements that are too infrequent, too insensitive, or too localized to provide conclusive evidence. geodesy will provide information that is crucial to understanding the physics of the earthquake process. The motivation for these measurements can be understood in the context of a simple model of the mechanical properties of the crust and upper mantle (Figure 3).

Rocks respond to applied stress in a way very similar to the children's toy, Silly Putty, i.e., they are viscoelastic. They respond elastically to rapid variations in stress, but undergo irreversible deformation by creeping flow under low but sustained applied stresses. If the stresses are high enough, rocks fail brittlely; the result of this sudden failure is an earthquake. Low temperature and low confining pressures favor brittle failure, while high temperatures promote creep by decreasing the effective viscosity of rocks. The rheological behavior also depends upon rock type, crustal rocks being more prone to creep than mantle rocks at the same ambient conditions. Pore fluids and volatiles also have effects. Although the details are poorly understood--indeed, an important goal of geodetic monitoring is to *obtain the observations needed to understand the details*--the general variation in effective strength of the crust and upper mantle is illustrated schematically in Figure 3.

Large earthquakes generally nucleate near one of the maxima in the strength versus depth curve and propagate rapidly through the adjacent brittle region. However, the deformation associated with an earthquake is not limited to this seismic rupture. Aftershocks typically relieve stress on slip-deficient areas of the fault plane and extend the rupture to adjoining regions. Aseismic creep on the fault plane, perhaps also extending into the ductile regime, may increase the total amount of displacement associated with an earthquake. Viscoelastic adjustments of the Earth's crust and mantle cause redistribution of strain after a major earthquake. Stress is relieved by flow in the ductile regions, allowing elastic strain to accumulate in the stronger, more elastic regions.

A general feeling for the interaction of the viscous and elastic properties of rocks in the crust and mantle may be obtained by considering the simple model originally developed by Elsasser (1969) and extended by others (e.g., Melosh, 1976; 1977, 1983; Cohen, 1984; Rundle and Jackson, 1977; Rundle, 1988a,b). This model consists of an elastic layer of thickness $h_e$ overlying a viscous layer of thickness $h_\nu$ and a rigid base. An initial sudden displacement of a fault diffuses outward with a diffusivity $\kappa = h_e h_\nu/\tau$, where $\tau$ is the Maxwell time of the system. Repeated jerky offsets on plate boundary faults result in very smooth motion some distance away, corresponding to the steady velocities of plate interiors.

For regional scale problems, such as southern California (Figure4), the elastic layer can be taken to be the upper crust, the viscous layer the lower crust, and the rigid substratum is the upper mantle. The displacement from an earthquake on a given fault will diffuse through the crust, causing regional strain and perhaps influencing other faults, on a time scale that depends upon the effective viscosity of the lower crust (e.g., Turcotte et al., 1984). Crustal rheology is poorly constrained, but reasonable estimates indicate that strains may propagate 30 km in 50 years. As can be seen from Figure 4, there have been many earthquakes in southern California in the past 50 years with significant source dimensions. Based on Elsasser's model, these events would be expected to have viscoelastic strain migration associated with them. Observing this strain migration could constrain crustal rheology.

Over a scale of tens of kilometers around the fault, Thatcher (1983) showed geodetic evidence for time-dependent strain rates after great earthquakes on the San Andreas. He showed that his rather sparse data could be fit both by a model in which a viscoelastic asthenosphere underlays an elastic lithosphere, and by a purely elastic model with exponentially-decaying afterslip on the fault. Thus, the change in strain rates could be due to the constitutive properties either of the fault zone or of the asthenosphere, but we do not know which. It is crucial to separate these effects in order to understand better the physics of earthquakes and transmission of stress through the crust. The distribution of postseismic strain in time and space would provide important constraints on the physics of faulting and on the material properties of the fault zone and surrounding Earth. Redistribution of stress and strain to adjacent faults would provide important information related to earthquake prediction.

We discuss below possible time-varying strains that might be observed following earthquakes in the context of specific recent experience in southern California. We then examine another possible source of time-dependent strain not associated with individual earthquakes.

**Post-seismic strains**. A variety of observations have made it clear that the extremely rapid strain of a fault rupture is followed by strain rates that are high, compared to the long-term average measured for the fault zone, but the data are lacking to determine the physics responsible. To begin closest to the fault, ruptures that break to the surface commonly show substantial slip in the hours and days after the actual earthquake. Does this reflect equal amounts of slip at greater depth, or is the deeper part of the fault stable, this afterslip merely being caused by the gradual propagation of deep slip through the near-surface layers?

A particularly clear example of this kind of ambiguity has recently been provided in southern California by the Superstition Hills earthquake sequence of November 1987. The first large event was the Elmore Ranch earthquake ($M_s$~6.2), followed 12 hours later by the main Superstition Hills event ($M_s$~6.6), and of course many aftershocks.

Seismicity patterns and surface rupture showed two conjugate faults, the Elmore Ranch earthquake being on a fault conjugate to the San Jacinto fault zone and the mainshock on a fault (Superstition Hills) parallel to the zone. Figure 4 shows the location of the Pinon Flat Observatory (PFO) relative to these conjugate events (labeled "1987").

We are fortunate to have available data from the long-base strain instruments at Pinon Flat Observatory (e.g., Wyatt et al., 1982); since these have been properly "anchored" to depth, they give results (out to periods of a year) that are better than any existing geodetic measurement. They thus provide a window, if only at one place, for what we might expect from future space-geodetic systems, and promise to be a source of "ground truth" for these measurements. Strains from these two events were recorded by two of the laser strainmeters at PFO; they are dominated by the coseismic offsets (e.g., Figure 5). These offsets and those recorded by other instruments at PFO are in reasonable agreement with results for a dislocation in a half-space, if seismically-derived parameters are used to define the dislocation. The frequent sampling of these data allows us to look at preseismic and postseismic deformations in some detail, with the best data coming from the fully-anchored NW laser strainmeter. During the interval between the two earthquakes, the largest signal on this record consists of microseisms plus some small residual drift in the instrument. We can certainly rule out any anomalous strains during this time above the level of about 3% of the eventual coseismic offset, and for the final 1000 seconds above about the 0.5% level.

It is hard to believe that the Superstition Hills earthquake was not triggered by the Elmore Ranch earthquake; but it is clear that no simple model of elastic strain and brittle failure can explain the 12-hour delay between events: if the Superstition Hills fault were close to failure, it should have ruptured during the dynamic strains generated by the Elmore Ranch earthquake, or at least soon after it, when the elastic stress changes had been fully imposed. We can think of several models, all speculative, to account for this.

1. All the surrounding material is elastic, and the Superstition Hills fault failed by brittle rupture at a critical stress level. The 12-hour delay was caused by afterslip on the Elmore Ranch fault; only after this had gone far enough was the applied stress sufficient for failure. This model would appear to be ruled out by the PFO data, which show no obvious afterslip (this would appear in proportion to the coseismic strain); any stress changes from this cause could be at most 10% of the stress changes at the time of the first earthquake. It could be that a small additional stress was enough, but this seems unduly *ad hoc*.

2. All parts of the system could have responded elastically, but the fault actually failed by some kind of stress corrosion. The model results of Tse and Rice (1986) show something like this; for a realistic friction law, earthquakes in their fault model begin with slow slip over a very small depth range, rapidly accelerating to seismic

slip, which would probably be consistent with the strainmeter data. However, this assumes a steady increase of applied stress; whether it still would result in inter-earthquake slip undetectable by the strainmeters would require additional modeling.

3. The Superstition Hills fault could have failed brittlely (as in the first hypothesis) with the delay between earthquakes being due to stress diffusion (Elsasser, 1969; Melosh, 1976, 1977, 1983) outward from around the Elmore Ranch fault. The physical model proposed recently by Rundle (1988a,b) may be invoked to account for the effects of interactions between faults (e.g., Rundle and Kanamori, 1987). We may assume that the first earthquake occurred in the brittle upper crust (Figure 4), underlain by a ductile lower crustal "asthenosphere." Just after the earthquake, the stresses in both regions are described by elasticity (for otherwise the coseismic strain step at PFO would not match the halfspace solution), but the ductile zone then begins to flow, interacting with the overlying elastic layer to cause a diffusion of stress outward from the fault, and hence increasing the stress on the Superstition Hills fault. For the usual estimates of crustal viscosity, we would expect little change in stress over 12 hours. If, however, the rheology is time-dependent or obeys power-law flow, the effective viscosity close to the fault (where the largest stress changes occur) could be quite low, allowing rapid diffusion of stress, which would tend to slow down as stress levels smooth out. Again, more detailed modeling will be needed to see if such stress diffusion could occur without causing strains in the overlying lithosphere large enough to be detected by the distant strainmeters at PFO.

Space Geodesy could have helped distinguish between these models, if measurements had been collected in the time interval between events. Multiple surveys of an array of monuments around these faults would have provided the best evidence possible on changes of strain between them,; had none been seen, we would have good evidence for some kind of delayed failure on the fault itself, rather than a delay from stress propagation. *It is crucial that planning for space-geodetic systems allow a fast enough response time to make critical observations like these possible.*

**Aseismic Deformations.** Aseismic deformations, in the form of strain episodes not associated with seismic events, have been hypothesized. One of the classic examples is the now infamous Palmdale Bulge. Repeat leveling of the region near Palmdale on the "Big Bend" segment of the San Andreas fault (see Figure 5) showed an apparent uplift of up to 30 cm, followed by subsidence (Castle et al., 1976). This feature has been interpreted to result from episodic slip on a horizontal slip zone in the lower crust (Thatcher, 1979; Rundle and Thatcher, 1980). It was later discovered that a least part of the inferred bulge was the result of atmospheric refraction errors (Holdahl, 1982), with an additional smaller error due to miscalibration of survey rods (Jackson et al., 1983). The revised amplitude of the uplift is close enough to measurement error to be ambiguous (Stein, 1987), leading some geophysicists to dismiss the entire phenomenon. The controversy still rages, pointing out the problems inherent in interpreting infrequent measurements where the tectonic signal expected is close to the noise level.

There is less controversial evidence from conventional laser trilateration surveys across the San Andreas fault near Palmdale for the existence of a strain event in 1979 (Savage and Gu, 1985). Their paper suggests a five year long period of strain accumulation perpendicular to the San Andreas which was recovered abruptly in a ~$10^{-6}$ strain event in 1979. Unfortunately, given the measurement error and the possible effects of aliasing on such sparse (~yearly) occupations, these results by themselves are not definitive. They are tantalizing, however, since completely independent observations suggest that these time-dependent strains may be real. Gravity (Jachens et al., 1983), water level in wells (Merifield et al., 1983), and seismicity (Sauber et al.,1983) in this region all showed unusual changes in 1979. There is a good correlation between variations in these quantities, suggesting that the changes are real, despite the relatively large uncertainties of the individual measurements. There is also intriguing structure in the various (sparse) time series, suggesting that there is time variation on time scales of a month or less that is missed by the rather infrequent measurements, i.e., that aliasing is a serious problem.

Jachens et al. (1983) compared variations in gravity, in dilatational strain, and in elevation (determined by repeat leveling) over several other areas of southern California. Their results show a remarkable tracking of variations in these quantities with relative amplitudes consistent with what is expected based on simple elastic compression, suggesting that they are real, with periods of from months to over two years. Unfortunately, the sampling is sparse enough in time that once again the possible effects of aliasing are a problem. Savage et al. (1987) also found evidence for a strain fluctuation in 1984, but comparisons of geodetic and strainmeter data strongly suggest systematic error in the former. In contrast, the data from PFO have never shown a strain change as large as discussed above, and in indeed the best records from fully-anchored instruments show that strain fluctuations are very small. We thus have several possibilities:

1. Strain fluctuations of sizes seen in 1979 (perhaps?) are fairly common in some regions (although the EDM data for southern California show only one event of this size), but have not been seen at PFO. It may be significant, for example, that Palmdale lies in the Big Bend region, where mantle convergence and downwelling may be occurring (e.g., Bird and Rosenstock, 1984; Humphreys et al., 1984), while PFO is in a simpler strike-slip regime. Or perhaps PFO is atypically quiet, somehow decoupled from its surroundings.

2. Large strain fluctuations occur, but are rare in time and localized over distances shorter than 100 km. Their absence at PFO thus is no more than a consequence of small-sample statistics.

3. The very small changes in strain seen at PFO are typical of most parts of southern California; strain accumulation is mostly steady. The 1979 episode is merely due to larger than expected instrumental error.

There is no way to settle this question without more frequent measurements over more baselines at higher precision, and this is what the next generation of space-geodetic systems will provide. Only with such systems will we be in a position to characterize and understand the *spatial distribution* and the *time dependence* of deformation within tectonic regions, from which constraints on the physics of the deformation process can be inferred.

## TYPES OF GEODETIC SIGNALS AND MEASUREMENT TECHNIQUES

The arguments presented so far lead us to conclude that the most significant departures from rigid-plate motions occur in zones of 100 to 1000 km width, within which differential motions are accommodated by a combination of seismic slip and aseismic deformation. However, because direct measurements of the kinematic evolution of geological systems using space-geodetic techniques can only cover time intervals of a few years, we are faced with the need to extrapolate these measurements to geological time scales in order to interpret them. In so doing, it is important to emphasize the space-time organization of geological systems and the processes that control their evolution. In fact, we seek a generic understanding of complex systems and their evolution, with special attention paid to transient behavior. If we are to trust the validity of extrapolations to geological time scales, a *process-oriented* approach appears to be superior to an *observation-driven* approach. Only then can we take full advantage of other data sources. These include, for example:

1. terrestrial geodesy, for which data sets spanning the last century are available (although not everywhere!) with dense spatial coverage (e.g., Snay et al., 1986).

2. classical geological techniques, which provide constraints pertinent to $10^3$-$10^6$ year time scales and more, and spatial scales ranging from local outcrops to continental dimension.

3. geophysical data and models, which help us understand the underlying physics, and formulate testable hypotheses.

In order to examine quantitatively the potential of present and future space-geodetic systems to contribute to the solution of geological problems, we consider on Figure 6 a simple map of various general types of geodetic signals, in terms of the spatial dimensions and temporal scales of the underlying physical phenomena. The time scales of interest range from seconds in the case of brittle seismic fracture to $10^6$ years for plate tectonics. Similarly, spatial scales to be considered range from a fraction of the crustal thickness to the dimensions of continents. We note that geological techniques are primarily useful to constrain phenomena mapped in the upper right corner of the graph, whereas the lower left corner is the realm of seismology. The vast domain occupying most of the figure is left for geodesists to study.

To compare this signal map with the capabilities of various geodetic tools, we use a very simple parametric model of the precision limit $\sigma$ of any given instrumental technique. Specifically, we assume that it is given by $\sigma^2 = \alpha^2 + (\beta\lambda)^2$, where $\alpha$ is a lower limit independent of the spatial scale (or "wavelength") $\lambda$ and $\beta$ is a coefficient of proportionality. Given this model, we examine the likelihood that a single event will be detected *and correctly characterized as to spatial and temporal scales* by selected techniques. The events considered here correspond to geodetic signals, expressed in terms of the displacement of a monument by a fixed fraction $\gamma$ of the spatial scale $\lambda$, over the time scale $\tau$. The model for $\sigma$ allows us to construct a detection map in the $(\lambda,\tau)$ plane. Estimates of $\alpha$ and $\beta$ yield the precision of a single observation, and, for simplicity, we take the noise to be Gaussian. In addition, we also truncate the detection maps according to the following considerations:

1. For any given technique, we assign a largest value of $\lambda, \lambda_{max}$, beyond which the technique is inapplicable or inaccurate, and a smallest value $\lambda_{min}$, below which *routine* deployment is probably not practical, because of logistical or cost considerations. In practice, we should truncate the map for values of $\lambda$ smaller than about twice the site spacing, corresponding to the spatial "Nyquist" wavenumber that could be resolved by the observations.

2. Similarly, the frequency of measurements allowed for each technique is not taken to be the highest frequency achievable, but a realistic re-occupation rate for a routinely re-surveyed network. Some notion of logistics and costs is therefore built into the detection map. The detection map is truncated for time scales smaller than that corresponding to the Nyquist frequency of the measurement time series, that is, for time scales smaller than twice the time interval between measurements.

3. Finally, although we allow some degree of noise reduction if repeated measurements are carried out, we limit the improvement to a maximum factor of 3, in view of the empirical observation that further statistical improvements are usually negated by uncontrolled systematic errors.

Figures 7 and 8 show the detection maps of various geodetic techniques for $\gamma = 10^{-7}$, and $\gamma = 10^{-8}$, respectively. These figures include detection maps for several existing systems, as well as two hypothetical ones, examined here for design purposes:

1. VLBI and SLR (for which we have assumed 3 measurements/year, with $\alpha = 1$ cm),

2. 1-color *Electronic Distance Measurement (EDM)*, (monthly measurements, $\alpha = 3$ mm and $\beta = 2 \times 10^{-7}$),

3. dedicated 2-color EDM (daily measurements, $\alpha = 0.2$ mm and $\beta = 10^{-7}$),

4. "observatory" measurements, i.e., continuously-recording strainmeters and tiltmeters,

5. a high precision, moderate frequency hypothetical system (weekly measurements, $\alpha = 1$ mm and $\beta = 10^{-8}$), and

6. a moderate precision, quasi-continuous hypothetical system (hourly measurements, $\alpha = 10$ mm and $\beta = 10^{-8}$).

As $\gamma$ decreases from $10^{-7}$ to $10^{-8}$, most detection curves appear to migrate toward the upper right, with the conspicuous exception of the observatory instruments. These instruments have red noise spectra, which is another way of saying that they drift by larger amounts over longer times; they are thus too unstable to detect small strains with long characteristic time scales. There is, in principle, no restriction in spatial scale, in the sense that an instrument measuring strain over a short distance will also respond to a strain change with much larger characteristic spatial scale. However, there is no way to recognize that a strain event is widespread with a single observatory of this type, so we truncate the curve for $\lambda$ on the order of the thickness of the elastic portion of the crust.

In both figures, it is clear that the hypothetical systems would fill a niche that no currently available geodetic technique is capable of filling. In particular, *if we can afford them,* either or both would permit investigations of the physics of earthquake coupling, and refinements of physical models of the spatial and temporal distribution of crustal strains that give rise to earthquakes. Whether we should prefer one over the other depends in part on the tradeoff that exists between the spatial and temporal scales we wish to investigate, but also very much on cost and ease of deployment. These diagrams illustrate the fact that space-geodetic techniques already have opened new windows for us to investigate tectonic phenomena, and that these windows will be even wider in the future.

## EXTRAPOLATION TO GEOLOGIC CONTEXT

Unlike the situation in oceanic lithosphere, plate boundary activity within the continental lithosphere is commonly distributed over broad zones up to several thousand kilometers wide, which consist of complex networks of faults and folds. In these areas, it is not unusual for extensional, thrust and strike slip faulting to occur contemporaneously within relatively small neighborhoods. Rotation of crustal fragments is common. Even seemingly undeformed areas are probably affected by considerable internal deformation and are only "undeformed" in relation to the more intense deformation occurring along their boundaries. Moreover, not all or even most faults within a given plate boundary deformation zone are active at any one time. Studies in the western U.S. and in China have shown that displacement may shift from one set of faults to another on a time scale of less than one million years, and perhaps as short as 100,000 years, even when rates of displacement on the individual faults are 10 mm/yr or greater.

This degree of spatial complexity and temporal variability limits the insight that even the most accurate geodetic measurements can, by themselves, provide into the nature of deformation of the continental crust. When deployed in such an environment, regional strain nets can at best resolve present-day rates of motion between various parts of a broad plate boundary, and without doubt this has to be a significant achievement in its own right. What regional strain nets cannot provide are the answers to fundamental questions about how strain is in fact accommodated, in what ways and how quickly the spatial distribution of deformation may change with time within a geologic system, and how mechanical and dynamical connections unify disparate types of deformation into a single coherent tectonic picture. However, in combination with other geological and geophysical information, accurate geodetic measurements using carefully positioned stations will provide an extremely powerful tool with which to address specific well-posed questions about crustal deformation in a particular tectonic setting.

Revisiting tectonic examples used earlier, we may raise questions pertaining to the dynamical mantle phenomena underlying the surface kinematics observed by geodesy. For instance, the role of upper mantle flow under Tibet is virtually unknown. It is not known if mantle flow occurs on the same scale as movements of crustal fragments, or if the scale of the mantle flow is comparable to the scale of the entire plate boundary collision zone. In the former case, one would expect zones of local mantle downwelling beneath regions of major crustal shortening in Tibet (such as below the Tien-Shan). In the latter case, movements of crustal fragments must occur within a thin sheet that is largely decoupled from the behavior of the upper mantle beneath it. If mantle flow can be linked spatially to the active movements of sizable crustal fragments, then one might reasonably infer that the same has been true throughout the history of the Tibetan Plateau. This would imply that temporal changes in mantle flow occur over the same time scale as changes in the direction and rate of movements within the crust, which can be dated using traditional geological techniques. Preliminary data from northeastern Tibet show that, on a length scale of tens of kilometers, major deformation has switched from one system of faults to another and from one type of deformation to another over time intervals of less than a million years (Zhang, 1987). If similar temporal variability in fault activity occurs at even larger scales in Tibet, then the time scale over which changes in crustal motion occur may be very short indeed. Alternatively, if mantle flow can be shown to be related to crustal motion only at the scale of the plate boundary as a whole, then little can be said about temporal variability of flow in the mantle from reconstructing crustal movement histories. One might, however, infer that such large scale flow would be likely to vary only over the same time scale as the overall plate boundary activity, roughly tens of millions of years (for example, England et al., 1985).

Similarly, in the case of the Mediterranean, questions aimed at understanding the interaction between active thrusting and extension, and which are amenable to study with geodetic and geologic data might include: How do rates of active convergence vary along the subduction boundaries? How does the rate and direction of active extension in "back arc" regions vary within the overriding plate? Is there a correlation between the rates and directions of extension and the rates and directions of convergence? Do major changes in rate coincide with structural features such as lateral offset or variations in trend of the convergent boundary? The answers to these and other questions about active crustal processes in these and similar systems elsewhere are essential if one seeks to evaluate the interaction between active crustal and mantle processes.

Comparable arguments can clearly be made in the case of the western U.S.; what the mantle flow is beneath southern California or beneath the Basin and Range are outstanding geophysical questions. The point made here is that, through geodesy and through geophysical techniques such as seismic tomography, one obtains but a "snapshot" of the present state of complex dynamical systems. The time scales that govern such systems can be short by geological standards, but are typically long, compared to the lengths of geodetic time series. In order to progress in our understanding of the physics, we must turn to a joint interpretation of geodetic observations, geophysical data and models, *and* geological reconstructions of past history. In fact, the understanding of crustal dynamics depends almost exclusively upon geologic data to characterize how deformation has evolved and been re-distributed over time. Prediction of crustal dynamic activity is not possible without a specific knowledge of regional geological context. Clearly, a broad range of techniques must be brought to bear on large scale tectonic problems. For instance, conventional geologic field studies are crucial for providing a detailed geological context, but such detailed studies cannot be made over large regions. Remote sensing, including structural geologic interpretation, mapping of lithologies and soils, and characterization of weathering surfaces (including relative dating of fault scarps) provides the key to an informed extension of detailed study results to regional scales.

## EMERGING LINES AND FUTURE DIRECTIONS

Strategy. Selection of a strategy for the continued development of space-geodetic solutions to outstanding geological problems in the next decade or two should be based on the recognition that resources and capabilities will remain finite, and in some instances, will be in fact somewhat limited. Consequently, we recommend the following guidelines:

1. **Focus on areas with major geological issues that require quantitative answers.** This entails the selection of areas and problems for which *testable* hypotheses can be formulated, together with a preferred focus on recognizable geological problems, for which other data sets of adequate quality are available. In addition, the socio-economic importance of the problem and the potential human impact of eventual solutions should be recognized and taken into consideration.

2. **Develop affordable technology.** This would have the desirable consequence that it would permit involvement of a greater proportion of the domestic and foreign scientific community. Further, it would allow improved spatial and temporal coverage within controlled costs, and often minimize the logistical burden of field work.

3. **Emphasize easily deployable systems.** In particular, we require a capability for *rapid* field deployment (on time scales of hours). Moreover, such systems would lead to lower personnel requirements, would allow easier access to remote areas, and would support both low resolution reconnaissance work, as well as detailed surveys of dense networks.

4. **Emphasize instrument calibration and measurement validation.** This entails the continued operation of the more burdensome, expensive systems at a level adequate to permit validation of results obtained by "lightweight" field systems. In addition, there will be a continued, and even enhanced need to maintain very high quality global and regional fiducial and reference networks. The systematic intercomparison of independent systems (e.g., VLBI, SLR, GPS) should be retained as an important validation technique, and we strongly recommend a careful examination of monumentation issues (particularly long-term stability), if future space-geodetic systems are used to monitor very large, dense networks.

<u>Point Positioning Objectives</u>. Scientific objectives for Point Positioning activities during the next decade include, for example:

1. to collect and analyze suitable "baseline" data to support the design and implementation of dense space-geodetic networks, to diagnose sources of geodetic noise, and to provide independent calibration and validation data;

2. to develop techniques for the *geological* interpretation of space-based ranging and altimetry data in plate-boundary deformation zones;

3. to formulate and attempt to solve significant problems in crustal deformation resolvable with the limited data (in time) that will be collected within the next decade.

Specifically, we should refine parameterized kinematic models of crustal deformation, and extend the analysis to include constraints from dense, frequently surveyed space-geodetic networks. At the same time, we must improve physical models of time-dependent deformation of the crust and upper mantle, and use these models in the planning of space-geodetic surveys and in the interpretation of the spatio-temporal strain patterns seen by space-geodetic techniques. Of fundamental importance for interpretation purposes will be the systematic comparison of space-geodetic observations to other, independent geophysical and geodetic data, such as observatory measurements of strain along short baselines, seismicity patterns, and other repeated geodetic and gravity surveys, in an effort to achieve a quantitative understanding of the phenomena which control volcanic and seismic cycles. As argued earlier, the elucidation of the time scales relevant to many important aspects of crustal dynamics will require integration of geodetic measurements with interpretations of local and regional geology. Finally, we will need to develop a systematic methodology for exporting approaches proven to be successful in a given region where accessibility is not an issue (e.g., the American west), to inaccessible regions with comparable or very different tectonic regimes (e.g., continental collision zones such as Tibet, trench boundaries such as the west coast of central and south America, strike-slip boundaries such as Turkey and New Zealand, and regions of back-arc deformation, such as the Aegean). Finally, in many instances, some of the critical structures will be submerged, so that a capability to locate precisely points on the seafloor relative to one another, and relative to a land-based geodetic network would be extremely valuable (e.g., Spiess, 1985).

## CONCLUSIONS AND RECOMMENDATIONS

Over the next decade and into the next century, the priorities we assign to various aspects of remote sensing applied to the study of the solid earth must acknowledge the tradeoff that exists between the application of recent advances in the technological aspects of space geodesy to solve urgent geological and geophysical problems, and the need to press ahead and develop new and better capabilities. The time scales associated with some of the most critical aspects of the current evolution of our environment are poorly understood, but are thought to be on the order of decades. Consequently, we may not have the luxury to defer practical applications until better technology is at hand, but should in many cases undertake systematic studies on an unprecedented global scale. Important conclusions reached in this section include:

1. To contribute to the improvement of existing models of present-day motion among the major plates, the tangential components of relative velocities on interplate baselines with endpoints located within stable plate interiors must be resolved to an accuracy of about 1 mm/yr.

2. The most important and interesting geodetic signals averaged over 1 hour to 100 years take the form of *departures* from predictions of million-year average rates based on geological rigid-plate models.

3. The most significant departures from rigid-plate motions occur in zones of 100 to 1000 km width, within which differential motions are accommodated by a *combination* of seismic slip and aseismic deformation.

4. Measuring velocities between crustal blocks to ±5 mm/yr will provide geologically useful constraints on the integrated deformation rates across continental plate-boundary zones, such as the western U.S. and Tibet.

5. It is only through the integration of geodetic and geologic field studies that active deformation can be related to earlier activity within an evolving tectonic system. Coordination of geodetic and geologic studies is therefore necessary to establish the temporal dependence of crustal deformation on a geologic time scale (e.g., Royden, 1988).

6. The establishment of frequently (or even continuously) surveyed local geodetic networks of sufficient density, around major geodetic sites in active areas, should receive high priority.

7. The development and systematic deployment of affordable and easily deployable space-geodetic systems with cm to mm precision and high sampling rates--that is, "occupation" frequency ranging from hourly to weekly--will permit investigation of geophysical phenomena, particularly the earthquake cycle, in a range of spatial and temporal scales never explored before.

8. Space-geodetic observations yield constraints on crustal kinematics; to achieve an improved understanding of the dynamics and thus, a better grasp of the underlying physical phenomena, we must rely on a broad combination of geophysical and geological observations as a way to extend the geodetic signals to longer time scales and to extrapolate surface information to crustal and mantle depths.

Based on the discussion held at the Erice workshop, and in view of the conclusions listed above, the panel on the "Long-Term Dynamics of the Solid Earth" formulated the following recommendations concerning the continued development and application of precise point positioning techniques:

*Over the next 20 years, major efforts in applying precise positioning techniques should be aimed primarily at:*

a. *Continued large scale* <u>*reconnaissance*</u> *surveys with station spacing on the order of $10^2$ km, to improve our understanding of the* *kinematic evolution of extensive, largely unexplored zones of continental deformation.*

*b. Sustained, repeated measurements of dense networks at centimeter-level accuracy, to determine the time dependence and spatial distribution of deformation within and across zones of intense tectonic activity. Measurement frequencies should range from daily to annually over a decade or more, with station spacing from 3 to 30 km, and network dimensions from 10 to 1000 km. In regions of complex deformation, geodetic measurements should be complemented by comprehensive tectonic and structural studies and careful estimates of displacements and displacement rates on geologic time scales.*

*c. Continued improvement of capabilities, to achieve:*

*--millimeter-level accuracy in both horizontal and vertical components for detailed subaerial studies, system calibration, and ultimately, low-cost routine deployment.*

*--centimeter-level accuracy in both horizontal and vertical components for sea-bottom systems.*

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TABLE 1. Types of motions at the earth's surface.

| | SECULAR | TRANSIENT |
|---|---|---|
| HORIZONTAL | Plate motions<br>Boundary-zone tectonics<br>Intraplate deformation | (Pre,co,post)-seismic<br>Fault creep<br>Stress redistribution |
| VERTICAL | Tectonic motions<br>Thermal subsidence<br>Diapirism<br>Crustal loading<br>Post-glacial rebound<br>Cratonic epeirogeny | (Pre,co,post)-seismic<br>Magma inflation<br>Tidal loading |

Table 2. Data sets used in successive generations of plate motion models

| | Magnetic rates | Transform faults | Slip vectors | Total data |
|---|---|---|---|---|
| 2nd generation, e.g. RM1[(1)], 1974 | 68 | 62 | 106 | 236 |
| 3rd generation, e.g. RM2[(2)], 1978 | 110 | 78 | 142 | 330 |
| 4th generation, NUVEL-1[(3)], 1988 | 277 | 121 | 724 | 1122 |

[(1)] Minster at al., (1974). [(2)] Minster and Jordan, (1978). [(3)] Gordon et al., (1988).

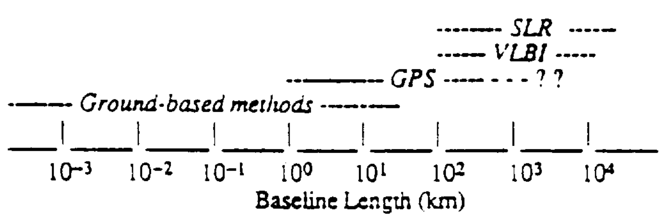


Figure 1 Spatial scales sampled by various geodetic methods.

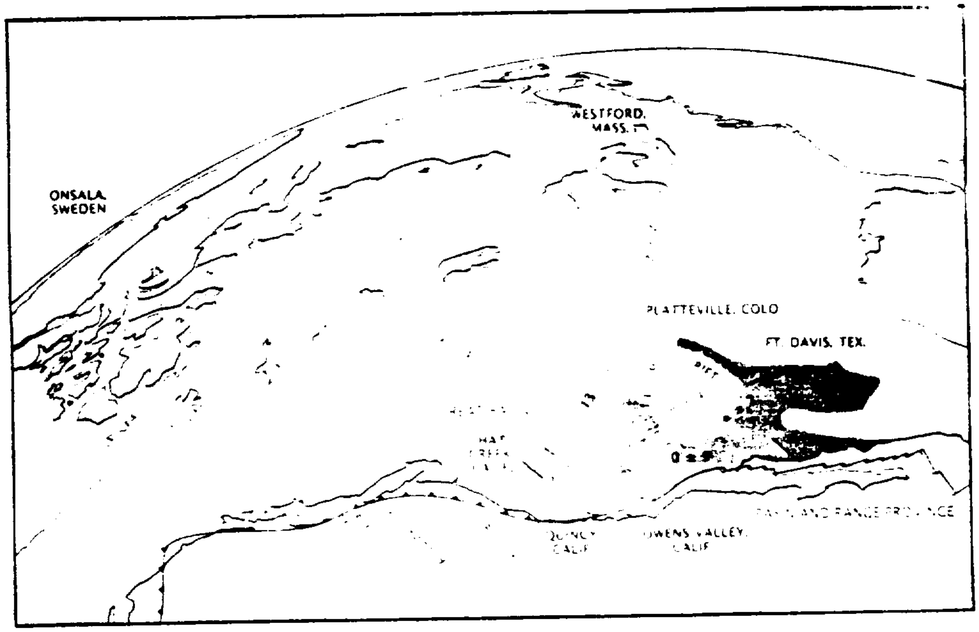


Figure 2. The San Andreas fault in central California is one element of the western U.S. plate boundary zone. In addition, we must account for contributions from crustal deformation both east and west of the fault. The integrated deformation west of the fault, which consists of NW-SE extension across the Great Basin, can be measured directly from the rates-of-change of VLBI baselines monitored by NASA's Crustal Dynamics Project. Combining this estimate with the geologically and geodetically observed rate of slip on the San Andreas, and the rigid-plate estimate of total motion between the Pacific and North America plates, we can derive geologically useful constraints on the integrated rate of deformation across the California margin, west of the fault. (From Jordan and Minster, 1988b. Reproduced with permission and by courtesy of *Scientific American*.)

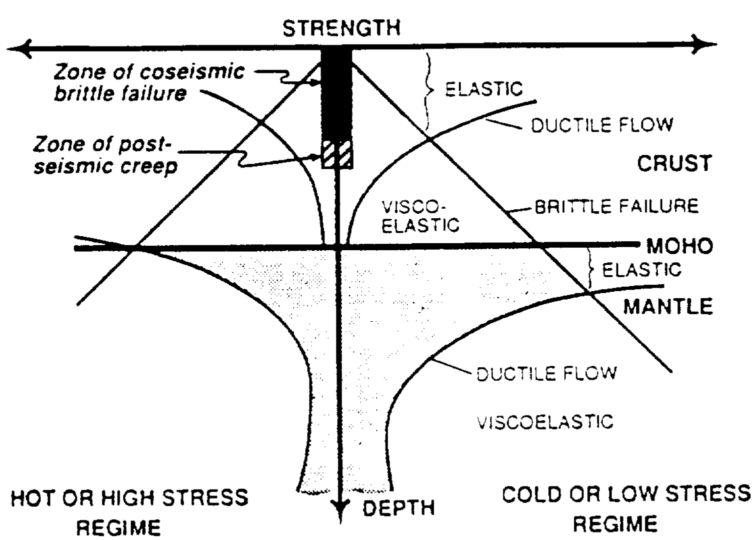


Figure 3. Schematic diagram of the strength and mode of deformation of the crust and upper mantle. Postseismic deformation occurs as the result of creep on the extension of the fault plane or stress relaxation in the viscoelastic regions.

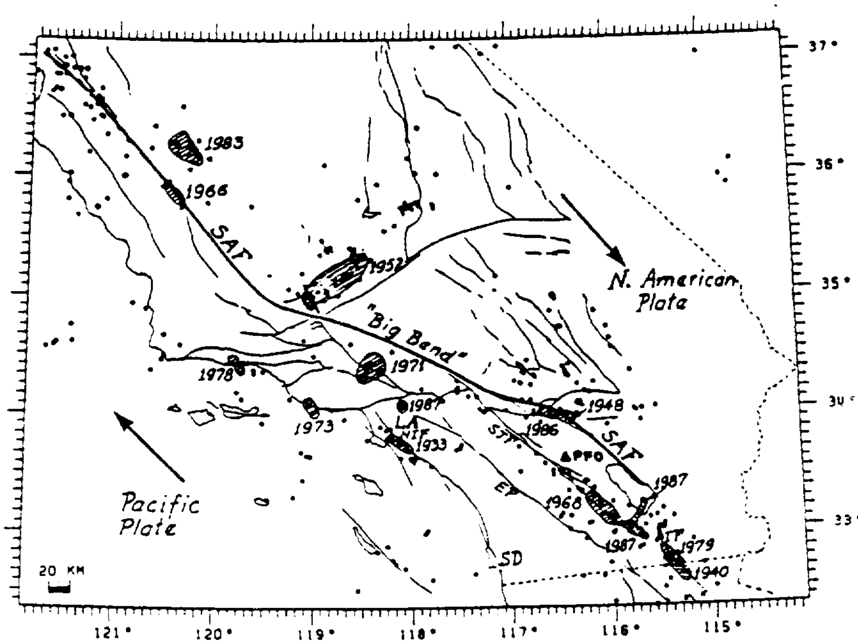


Figure 4. Major fault lines and earthquake epicenters in southern California. All events of magnitude >4.5 in the past 55 years are shown, with rupture zones of the largest events shaded. Fault abbreviations SAF, San Andreas; SJF, San Jacinto; EF, Elsinore; NIF, Newport-Inglewood; GF, Garlock; and IF, Imperial. PFO is the Pinon Flat Observatory.

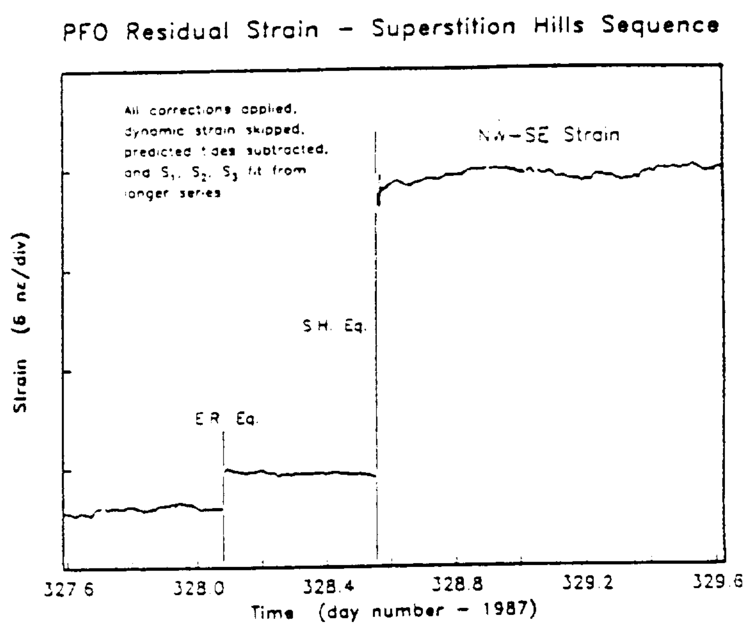


Figure 5. Superstition Hills events recorded at The Piñon Flat Observatory (See Figure 4).

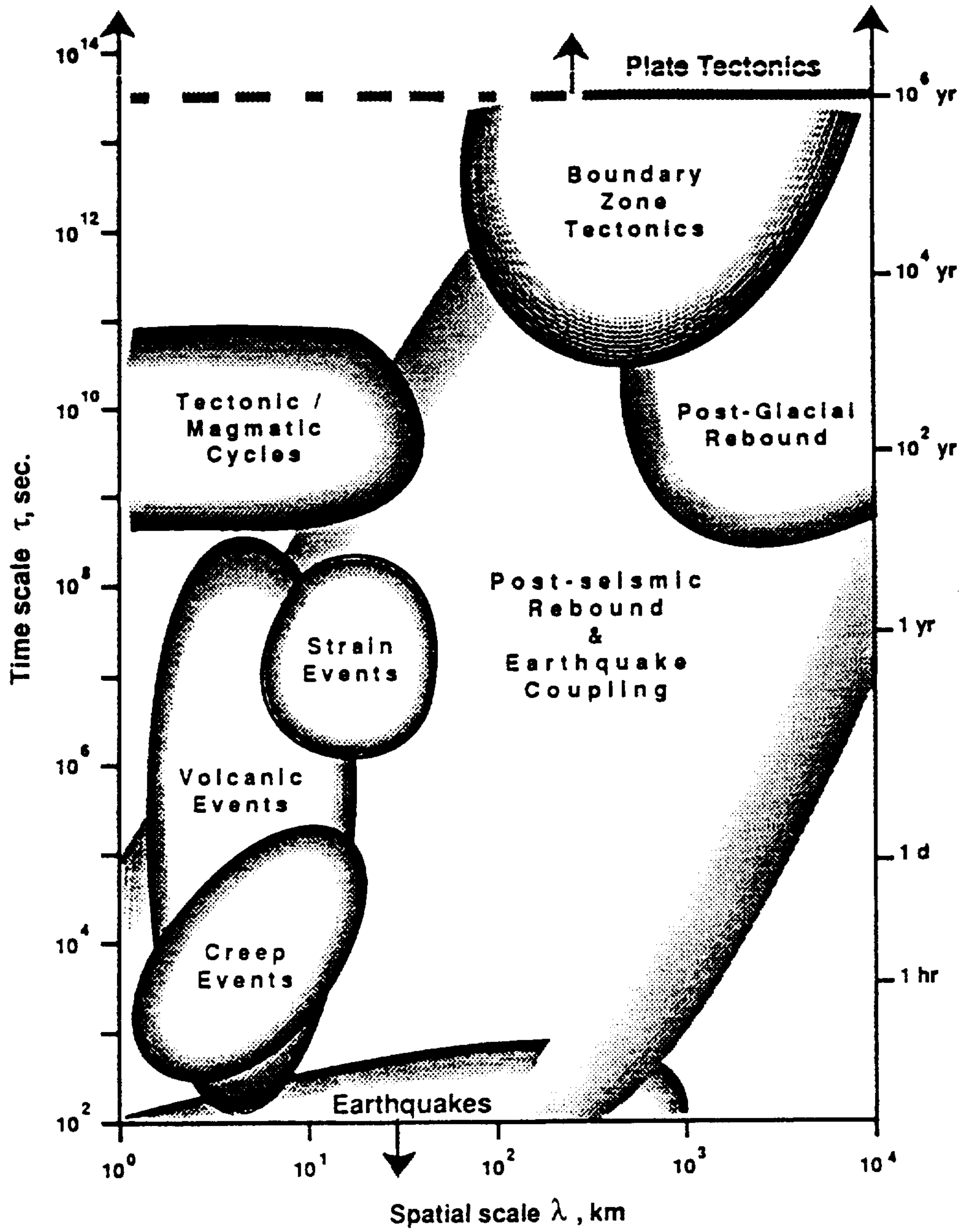


Figure 6. Map of geodetic signals in terms of spatial and temporal scales.

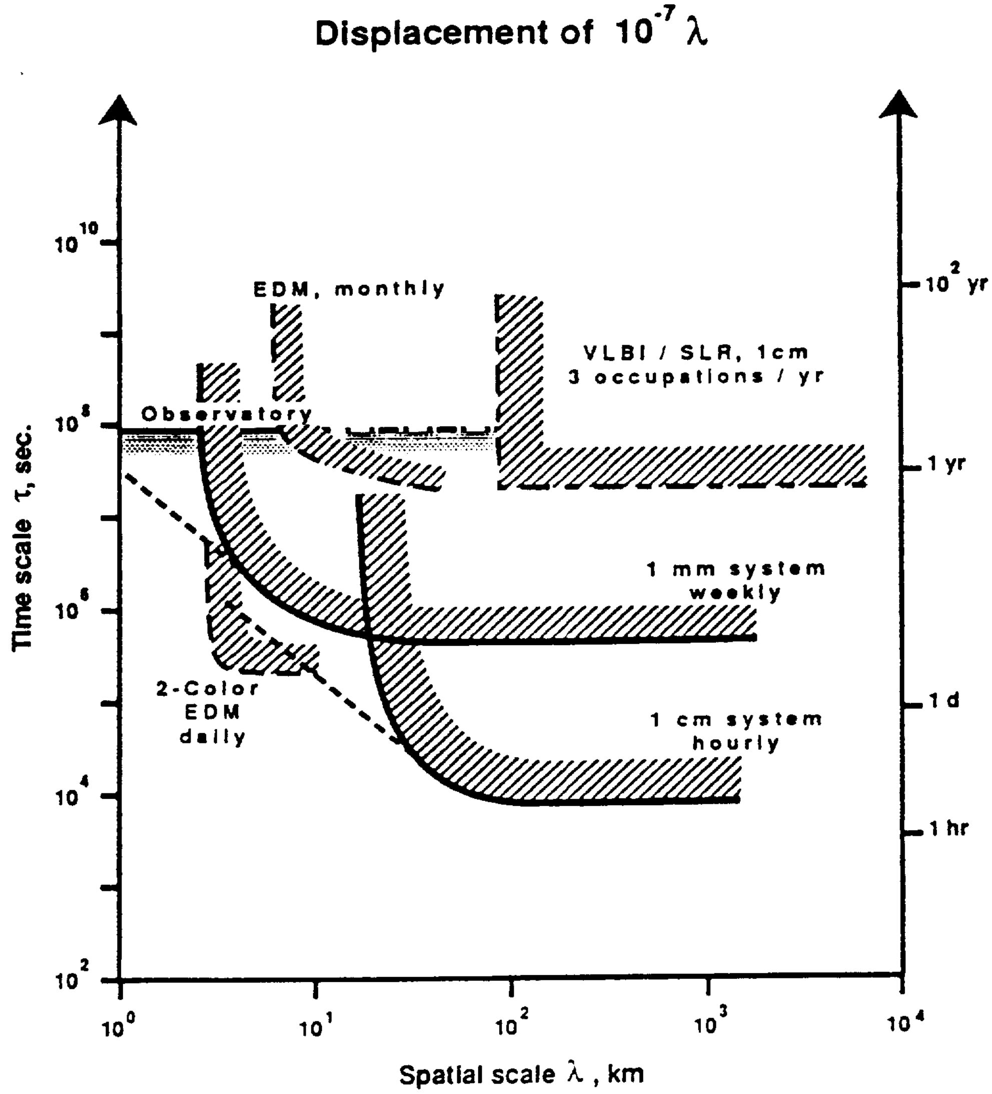


Figure 7. Detection capability of various geodetic techniques at the $10^{-7}$ strain level.

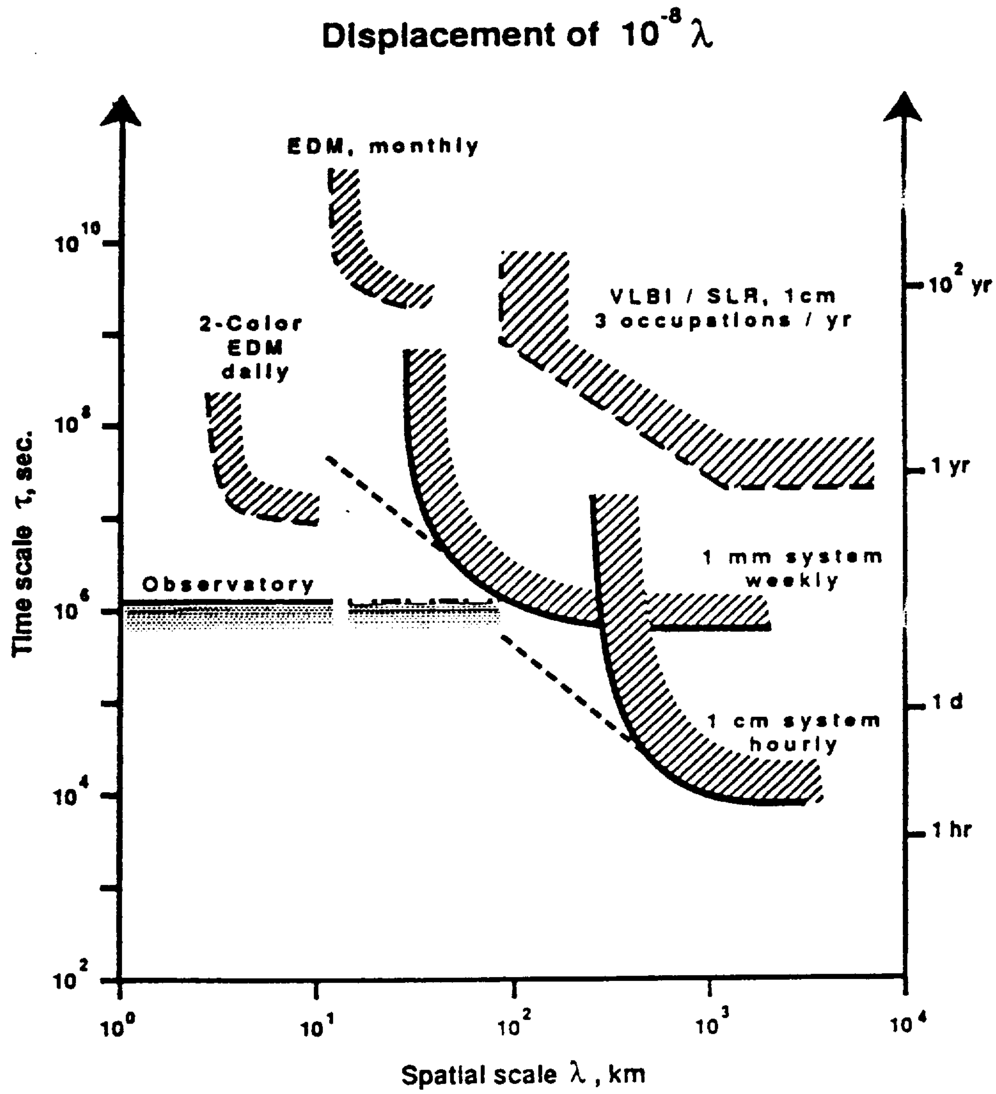


Figure 8. Detection capability of various geodetic techniques at the $10^{-8}$ strain level.

Table 3. EULER vectors for the rigid-plate model NUVEL-1 (from Gordon et al., 1988)

| Plate Pair | Latitude °N | Longitude °E | $\dot{\omega}$ (deg/My) | Error Ellipse $\sigma_{max}$ | $\sigma_{min}$ | $\zeta_{max}$ | $\sigma_{\omega}$ (deg/My) |
|---|---|---|---|---|---|---|---|
| | | | *Pacific Region* | | | | |
| na-pa | 48.7 | -78.2 | 0.78 | 1.3 | 1.2 | -61 | 0.01 |
| co-pa | 36.8 | -108.6 | 2.09 | 1.0 | 0.6 | -33 | 0.05 |
| co-na | 27.9 | -120.7 | 1.42 | 1.8 | 0.7 | -67 | 0.05 |
| co-nz | 4.8 | -124.3 | 0.95 | 2.9 | 1.5 | -88 | 0.05 |
| nz-pa | 55.6 | -90.1 | 1.42 | 1.8 | 0.9 | -1 | 0.02 |
| nz-an | 40.5 | -95.9 | 0.54 | 4.5 | 1.9 | -9 | 0.02 |
| nz-sa | 56.0 | -94.0 | 0.76 | 3.6 | 1.5 | -10 | 0.02 |
| an-pa | 64.3 | -84.0 | 0.91 | 1.2 | 1.0 | 81 | 0.01 |
| pa-au | -60.1 | -178.3 | 1.12 | 1.0 | 0.9 | -58 | 0.02 |
| eu-pa | 61.1 | -85.8 | 0.90 | 1.3 | 1.1 | 90 | 0.0[illegible] |
| co-ca | 24.1 | -119.4 | 1.37 | 2.5 | 1.2 | -60 | 0.06 |
| nz-ca | 56.2 | -104.6 | 0.58 | 6.5 | 2.2 | -31 | 0.04 |
| | | | *Atlantic Region* | | | | |
| eu-na | 62.4 | 135.8 | 0.22 | 4.1 | 1.3 | -11 | 0.01 |
| af-na | 78.8 | 38.3 | 0.25 | 3.7 | 1.0 | 77 | 0.01 |
| af-eu | 21.0 | -20.6 | 0.13 | 6.0 | 0.7 | -4 | 0.02 |
| na-sa | 16.3 | -58.1 | 0.15 | 5.9 | 3.7 | -9 | 0.01 |
| af-sa | 62.5 | -39.4 | 0.32 | 2.6 | 0.8 | -11 | 0.01 |
| an-sa | 86.4 | -40.6 | 0.28 | 3.0 | 1.2 | -24 | 0.01 |
| na-ca | -74.3 | -26.1 | 0.11 | 25.5 | 2.6 | -52 | 0.03 |
| ca-sa | 50.0 | -65.3 | 0.19 | 15.1 | 4.3 | -2 | 0.03 |
| | | | *Indian Ocean and African Regions* | | | | |
| au-an | 13.2 | 38.2 | 0.68 | 1.3 | 1.0 | -63 | 0.00 |
| af-an | 5.6 | -39.2 | 0.13 | 4.4 | 1.3 | -42 | 0.01 |
| au-af | 12.4 | 49.8 | 0.66 | 1.2 | 0.9 | -39 | 0.01 |
| au-in | -5.5 | 77.1 | 0.31 | 7.4 | 3.1 | -47 | 0.07 |
| in-af | 23.6 | 28.5 | 0.43 | 8.8 | 1.5 | -74 | 0.06 |
| ar-af | 24.1 | 24.0 | 0.42 | 4.9 | 1.3 | -65 | 0.05 |
| in-eu | 24.4 | 17.7 | 0.53 | 8.8 | 1.8 | -79 | 0.06 |
| ar-eu | 24.6 | 13.7 | 0.52 | 5.2 | 1.7 | -72 | 0.05 |
| au-eu | 15.1 | 40.5 | 0.72 | 2.1 | 1.1 | -45 | 0.01 |
| in-ar | 3.0 | 91.5 | 0.03 | 26.1 | 2.4 | -58 | 0.04 |